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1 Screening and techno-economic assessment of
2 biomass-based power generation with CCS technologies
3 to meet 2050 CO₂ targets

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20 **Abstract**

Biomass-based power generation combined with CO₂ capture and storage (Biopower CCS) currently represents one of the few practical and economic means of removing large quantities of CO₂ from the atmosphere, and the only approach that involves the generation of electricity at the same time. We present the results of the *Techno-Economic Study of Biomass to Power with CO₂ capture (TESBiC)* study, that entailed desk-based review and analysis, process engineering, optimisation as well as primary data collection from some of the leading pilot demonstration plants. From the perspective of being able to deploy Biopower CCS by 2050, twenty eight Biopower CCS tech-

nology combinations involving combustion or gasification of biomass (either dedicated or co-fired with coal) together with pre-, oxy- or post-combustion CO₂ capture were identified and assessed. In addition to the capital and operating costs, techno-economic characteristics such as electrical efficiencies (LHV% basis), Levelised Cost of Electricity (LCOE), costs of CO₂ captured and CO₂ avoided were modelled over time assuming technology improvements from today to 2050. Many of the Biopower CCS technologies gave relatively similar techno-economic results when analysed at the same scale, with the plant scale (MW_e) observed to be the principal driver of CAPEX (£/MW_e) and the cofiring % (i.e. the weighted feedstock cost) a key driver of LCOE. The data collected during the TESBiC project also highlighted the lack of financial incentives for generation of electricity with negative CO₂ emissions.

1 *Keywords:* Biomass, biopower, bioenergy, power generation, carbon
 2 capture and storage (CCS), scenarios and forecasting, techno-economics

3 **1. Introduction**

4 The International Energy Agency (IEA) has warned that the door to
 5 limiting global average temperature rises to only 2°C (over pre-industrial
 6 levels) is closing, and the International Panel on Climate Change (IPCC)
 7 has highlighted the urgency of taking immediate mitigation actions in terms
 8 of technological changes [1, 2]. This means that technologies that can rapidly
 9 remove vast amounts of CO₂ from the atmosphere may therefore need to be
 10 deployed, if other mitigation measures fail to rapidly reduce global emissions
 11 - a fact emphasised in the recent IPCC report which also placed an unprece-

1 dented emphasis explicitly on Bio-energy with carbon capture and storage
2 (BECCS) [3].

3 BECCS or BioCCS as a concept can be achieved via multiple applica-
4 tions, i.e. through power generation (Biopower), biofuels production, hy-
5 drogen plants, bio-synthetic natural gas, heating, and industrial processes
6 (steel, cement and paper) [4, 5, 6, 7, 8]. In case of BECCS, the emissions
7 reduction potential is largely dependent on the scale of the installation and
8 the upstream biomass emissions, which is in turn dictated by the available
9 scale of the component technologies and the availability of biomass feedstock.
10 Despite potential risks of over-reliance of as yet unproven technology, due to
11 its large-scale negative emissions potential, BECCS presents a high value op-
12 tion that persistently features in majority of recent cost-effective scenarios
13 or pathways aimed at decarbonising global energy use and achieving climate
14 change targets [9, 10, 11, 12, 13, 14, 15]. Recently, linear programming was
15 applied to conduct global modelling of various renewable technologies, in-
16 cluding BECCS over the period 2010 to 2050 [16]. For the zero emissions
17 scenario, BECCS was concluded to play a vital role in satisfying the demand
18 in the heat sector. Elsewhere, the global technical potential of negative CO₂
19 emissions from BECCS, if deployed, has been estimated to be in the range
20 of 3.2 to 10.4 Gt CO₂e/yr [17, 18]. BECCS has been reviewed at a systems-
21 level in order to assess its role in stabilising CO₂ concentrations [19]. Based
22 on an assumption of a global biomass potential of 100 EJ/yr, the review
23 [19] stated a technical potential for BECCS at 10 GtCO₂/yr in 2050, with
24 an economic potential of around 3.5 GtCO₂/yr. In another study, an en-
25 ergy system optimisation approach has been adopted to analyse the role of

1 BECCS in meeting various global mean temperature limits [20]. Given its
2 negative carbon emissions potential, BECCS allowed for lower temperature
3 targets to become attainable and also at lower costs. At the same time, the
4 uncertainties and knowledge gaps with respect to BECCS as a mitigation
5 technology have also been highlighted. Some of the uncertainties include the
6 sustainability of large scale deployment relative to other land and biomass
7 needs (with significant concerns over land-use implications), the availabil-
8 ity of suitable and secure CO₂ sequestration sites globally, the response of
9 natural land and ocean carbon sinks to negative emissions, plus the costs,
10 financing, legal liabilities and public acceptance [20, 19, 21, 22].

11 Currently, four BioCCS projects are in operation around the world -
12 mostly focused on CO₂ capture from ethanol production, and three of the
13 projects use the CO₂ for enhanced oil recovery [19]. Recently, a spatially
14 explicit optimisation framework was developed to characterise the optimal
15 sizing (scale) for potential BECCS facilities located in Illinois, USA [23]. It
16 was assessed that the biomass supply, technology cost and cost scaling have
17 a strong effect on the optimal capacity, however the levelised cost and the
18 cost of avoided CO₂ were observed to be relatively insensitive to deviations
19 from the scaled size.

20 The present paper focuses on the assessment of the application of BECCS
21 specifically in the biopower generation industry. For a biopower application,
22 coupling CCS technology with a co-fired (biomass and coal) power plant
23 offers a practical option with moderate investment costs to evaluate these
24 technology combinations. The significant research, development and inno-
25 vation efforts in the field of CCS have already been reviewed in detail else-

1 where [24, 25, 26, 27, 28]. The strong potential of *Biopower CCS* for carbon
2 abatement has also been recognised in several studies, while highlighting the
3 dearth of comprehensive data and techno-economic uncertainties associated
4 with Biopower CCS [29, 14, 17, 18, 19, 30, 31, 32, 33, 34]. In the context of
5 UK, the significance of including Biopower CCS within the energy mix in or-
6 der to achieve the UK target of a 80% reduction in greenhouse gas emissions
7 by 2050 in a cost-effective manner, has been emphasised by the Committee
8 on Climate Change and the Energy Technologies Institute [35, 36].

9 In this paper, we discuss some of the key results from a study that was
10 commissioned by the Energy Technologies Institute (ETI) in the UK, to
11 assess the techno-economics of a wide range of technology combinations in-
12 volving biomass fuelled power generation combined with CO₂ capture. This
13 *Techno-Economic Study of Biomass to Power with CO₂ capture (TESBiC)*
14 study entailed desk-based review and analysis, numerical modelling, optimi-
15 sation as well as data collection at some of the leading pilot demonstration
16 plants in Europe. Twenty eight Biopower CCS technology combinations
17 were identified and assessed as part of the TESBiC study. The paper is
18 organised as follows: First, a short overview of the work performed in the
19 field of Biopower CCS is given. Then the technical approach adopted in the
20 TESBiC project is presented, followed by one workflow example of a specific
21 Biopower CCS technology. The results of the techno-economic analysis of the
22 eight short-listed Biopower CCS technology combinations are then discussed
23 before drawing final conclusions.

2. Overview of Biopower CCS

From the perspective of deployment of Biopower CCS by 2050, numerous technology combinations involving combustion or gasification of biomass (either dedicated or co-fired with coal) together with pre-, oxy- or post-combustion CO₂ capture currently exist. In a life cycle assessment (LCA) study of biomass co-firing power plants with CCS, a supercritical pulverised coal (PC) with post-combustion CO₂ capture and an integrated gasification plant with pre-combustion capture were analysed at a common capacity of 550 MWe and the gains made in terms of reduction of CO₂ and SO₂ emissions were weighed against the efficiency drop and increased infrastructure demand [33]. For a fixed co-firing of 30% (energy basis) and the extent of CO₂ capture set at 90%, net negative emissions in the range of 67-85 g/kWh were reported. In a separate techno-economic analysis conducted [37], the potential of dedicated biomass with integrated gasification combined cycle (IGCC) coupled with CCS was proposed as the main bionergy conversion technology for the long term, representing 33% of the global mitigation potential by 2100. An integrated gasification facility that combined electricity generation (combined cycle) and an option to produce Fischer Tropsch Diesel, with and without CCS has also been assessed in another study [38]. Torrefied biomass was proposed as a feedstock for the facility and specific direct CO₂ emissions were estimated to be -0.93 kg CO₂/kWh. A cofired (80% coal and 20 biomass) IGCC based on entrained-flow gasifier designs combined with oxy-, pre- and post-combustion CO₂ capture at a fixed rate of 90% has also been modelled [39]. It was concluded that the iron-based chemical looping was significantly more energy efficient than the post- and pre-combustion

1 capture systems. Furthermore, the study also indicated that pre-combustion
2 capture using either physical or chemical solvents was more energy efficient
3 than post-combustion capture using chemical solvents.

4 Elsewhere, a mixed integer nonlinear programming (MINLP) approach
5 was adopted to emphasise the need for operating biomass co-fired power
6 plants at a high load factor and at high levels of the extent of CO₂ capture
7 to ensure commercial feasibility [40]. Under the conditions of constrained
8 supply of indigenous biomass, a price range threshold of 120-175 £/t of CO₂
9 was reported to incentivise the generation of carbon negative electricity. Re-
10 cently, biomass conversion has also been considered in large scale (660 MWe)
11 co-fired biomass plants retrofitted with post-combustion CO₂ capture and
12 relatively smaller scale (100 MWe) dedicated biomass plants equipped with
13 CO₂ capture [41]. For a 90% CO₂ capture, the power generation efficiency
14 drop with CCS was estimated to be 10% points. For such efficiency penalty
15 with CCS, the importance of ensuring a sufficiently high initial net efficiency
16 of the basic biopower plant was highlighted and the advantages offered by
17 the large scale co-fired power plant with super critical steam power cycles
18 were also emphasised.

19 **3. Approach**

20 Twenty eight Biopower CCS technology combinations involving combus-
21 tion or gasification of biomass (either dedicated or co-fired with coal) together
22 with pre-, oxy- or post-combustion CO₂ capture were examined based on the
23 following assessment criteria over the period 2010 to 2050:

- 24 • Techno-economic characteristics such as nameplate capacities, capacity

- 1 factors, LHV% electrical efficiencies, extent of co-firing and of CO₂
2 capture;
- 3 • CO₂, SO₂ and NO_x emissions;
 - 4 • capital and operating costs (CAPEX and OPEX);
 - 5 • Levelised costs of electricity (LCOE), costs of CO₂ captured and avoided;
 - 6 • Flexibility and load-following capabilities;
 - 7 • Technology Readiness Level (TRL) progressions;
 - 8 • Feedstock characteristics;
 - 9 • Gaps in the current understanding, resulting technical and commercial
10 risks and corresponding potential mitigation strategies;
 - 11 • UK development prospects; and
 - 12 • Intellectual property and UK deployment potentials.

13 Bearing in mind the challenges arising from the lack of Biopower CCS
14 data in the public domain and the large variances in the technology readiness
15 levels (TRLs) of the various CO₂ capture technologies (Figure 1), significant
16 consideration was given to the approach adopted in terms of the technology
17 landscape review, screening, model development and the ensuing analysis
18 phases.

19 [Figure 1 about here.]

1 Furthermore, to help ensure that the overall economic parameters could
2 be compared across the technology combinations, harmonised estimates for
3 a number of the more common cost items of equipment and utilities were
4 prepared for use in this work. For example, the additional capital costs in
5 terms of operations and utilities were assumed to be 5% of the total installed
6 CAPEX, with civils and land set at 10%, project development at 5% and
7 contingency at 10%. Several pieces of common equipment (compressors, air
8 separation, turbines) also had their costs harmonised. Feedstock prices (2010
9 basis) were set throughout at 7 £/MWh for bituminous coal, 27 £/MWh for
10 traded wood pellets and 10 £/MWh for domestic wood chip, with plant
11 utilisation factors all set to 85%. Note that it was assumed that Biopower
12 CCS will take the role of providing baseload power and will not play a role
13 in balancing UK power grid with high penetration of renewables. The fixed
14 operating costs were assumed to be 5% of the total installed CAPEX (based
15 on 4% labour and maintenance and 1% for insurance). Most importantly, all
16 costs are presented as "Nth-of-a-kind" (as if the technology were already at
17 TRL 9), and not prototype costs (e.g. current lower TRLs).

18 A schematic of the approach used within the TESBiC project is presented
19 in Figure 2. A landscape review of twenty eight technology combinations was
20 performed based on data from the project partners and from literature, plus
21 a review of existing roadmaps in the energy and CCS fields. Note that only
22 those options able to reach TRL 5 (pilot scale) by 2020 were considered
23 likely to be advanced enough to be able to contribute to mass deployment
24 in the UK by 2050. This screening criterion was based on typical industry
25 lead times and assuming that no major concerted focused effort in terms

1 of research, development and deployment was made in advancing specific
2 technology. Note that waste-to-energy plants were not considered, given
3 their significantly lower efficiency and limited future deployment potential
4 as compared to dedicated or cofiring biomass plants, thus weakening the
5 case for adding efficiency-penalising capture [41, 42]. Fuel cells offer another
6 power generation option compared to combined cycle hydrogen turbines, but
7 as they would use the same biomass gasification and pre-combustion capture
8 technologies as a dedicated biomass integration gasification combined cycle
9 (bio IGCC) plant, these were not focused upon within the TESBiC study.
10 Biomass integrated gasification fuel cell (BIGFC) technology is currently
11 around TRL 4-5, but combined with CCS the whole system TRL is below
12 TRL4 [43, 44].

13 As a consequence of the landscape review and screening, the following
14 eight technology combinations were selected for further more detailed anal-
15 ysis:

- 16 1. Biomass-coal co-firing combustion, with post-combustion amine scrub-
17 bing (*cofire amine*)
- 18 2. Dedicated biomass combustion with post-combustion amine scrubbing
19 (*bio amine*)
- 20 3. Biomass-coal co-firing combustion, with post-combustion carbonate loop-
21 ing (*cofire carb loop*)
- 22 4. Biomass-coal co-firing oxy-combustion, with cryogenic O₂ separation
23 (*cofire oxy*)
- 24 5. Dedicated biomass oxy-combustion, with cryogenic O₂ separation (*bio*
25 *oxy*)

2020, 2030, 2040 and 2050 for all eight technology combinations. Significant increases in the electricity generation efficiencies and reductions in the capital costs of all of the technologies were projected for the period 2010 to 2050. By their nature, these projections have large uncertainties attached, although the level of optimism assumed within the TESBiC project was consistent with that in other industry data sources used.

4. A work-flow example

In this section, the technical work-flow employed during the assessment of the Biopower CCS technologies is described with the help of a specific technology combination, chosen as an example. Given the paucity of published data on low TRL (TRL4) technology options, dedicated biomass chemical looping (bio chem loop) has been considered here.

Figure 3 shows a high-level process flow description for bio chem loop at a base capacity of 268.3 MW_e. Mass and energy balance calculations were used to evaluate the techno-economic output metrics (e.g. LHV efficiency, CAPEX, OPEX, etc.) at a number of operating points, termed as base cases.

[Figure 3 about here.]

The base case models were then used to populate data for the formulation of computational surrogates or meta models. The meta-model utilised was of the form, as given in Equation (1):

$$y_m = \bar{y}_m + A_{mn}(x_n - \bar{x}_n) \quad (1)$$

1 where the output vector y_m is related to an input vector x_n through
 2 a coefficient matrix A_{mn} in a piecewise linear fashion by difference from a
 3 base input vector \bar{x}_n and a base output vector $\bar{y}_m = f(\bar{x}_n)$, and where m
 4 indicates the output index and n , the input index. Parameter estimation
 5 was performed with the Model Development Suite (MoDS) software [45] to
 6 calibrate the meta models via the coefficient matrix A_{mn} to base case eval-
 7 uations obtained from the detailed models. The MoDS software has been
 8 previously applied for various digital engineering tasks that include param-
 9 eter estimation and uncertainty quantification [46], Design of Experiments
 10 (DoE) [47], surrogates or meta model generation [48] and global sensitivity
 11 analysis [49, 50].

12 **5. Results and discussion**

13 Biopower CCS technologies currently represent one of the very few prac-
 14 tical and economic means of removing large quantities of CO₂ from the atmo-
 15 sphere, and uniquely involves the generation of electricity at the same time.
 16 This would appear to make this approach to power generation very attractive
 17 given that many industrialised countries have stringent targets for the reduc-
 18 tion of CO₂ emissions. It is clear, however that the available Biopower CCS
 19 technologies are relatively expensive in terms of both capital and operating
 20 costs (thus requiring financial incentives) as compared to fossil fuel based or
 21 other renewable power generation. Presently, there are no specific financial
 22 incentives anywhere in the world for the generation of electricity specifically
 23 with negative CO₂ emissions. Overall, the data collected during the TES-
 24 BiC project indicated that the most significant barriers to the deployment

1 of Biopower CCS technologies will be economic and regulatory in nature,
2 rather than technical, provided that fossil CCS technology is deployed at
3 commercial scale.

4 Key performance parameters in terms of the generation efficiency (LHV%
5 basis) and the specific investment costs (CAPEX) for the eight Biopower CCS
6 technology combinations were benchmarked at common plant scales (of 50
7 MW_e and 250 MW_e). Figure 4 gives the efficiency and CAPEX results at 50
8 MW_e plant capacity.

9 [Figure 4 about here.]

10 Bio amine and bio oxy technologies were the least efficient options, whereas
11 cofire and bio IGCC showed the potential to reach the highest efficiencies
12 by 2050. Although the efficiency of cofire carb loop remained competitive,
13 the CAPEX was relatively high. Alongside the cofire amine and cofire oxy
14 options, bio chem loop yielded the relatively lowest CAPEX range at a mod-
15 erately high efficiency.

16 Wherever a direct comparison was feasible (for plants with an unabated
17 equivalent), it was observed that the net efficiency penalty due to carbon
18 capture varied in the range of 6 to 15 percentage points, whereas the spe-
19 cific investment costs (CAPEX) increased significantly in the range 45% to
20 130%, with annual operating and maintenance costs growing by 4% to 60%.
21 In case of dedicated bio chem loop, however, there is no efficiency loss or
22 comparator given that both power generation and CO₂ capture are intrin-
23 sic to the operation of the technology. At 250 MW_e, the technologies were
24 observed to be tightly grouped, almost lying completely within each other's

1 uncertainty bounds. These observations confirm that within the current un-
2 certainty bounds of the available data, the plant scale (MW_e) is the principal
3 driver of CAPEX ($\text{£}/\text{MW}_e$), rather than the choice of technology, with larger
4 plants having lower specific capital costs.

5 [Figure 5 about here.]

6 The LCOE was calculated using a discounted cost of capital (at 10%
7 discount rate, and a plant technical/economic lifetime of 30 years), adding
8 the annual fixed and variable operating costs, and finally adding the feed-
9 stock costs divided by the plant electricity generation efficiency. Figure 5
10 presents the potential evolution of the LCOE at a 50 MW_e scale for the
11 eight technologies covering the period up to 2050. Three distinct groupings
12 can be observed, with low efficiency bio amine and bio oxy with the highest
13 LCOE, then the higher efficiency bio IGCC, bio chem loop and cofire carb
14 loop options in the middle, and lastly, the cofire amine, cofire oxy and cofire
15 IGCC with the lowest LCOE (attributed to cheap coal prices). Since this
16 is a small-scale plant, either biomass pellets or chips could realistically be
17 used, however Figure 5 shows the LCOE results when the biomass feedstock
18 used is in the form of imported pellets. The switch to using chips instead of
19 pellets dramatically lowers the LCOE, with many options having very simi-
20 lar LCOE (80-100 $\text{£}/\text{MWh}$) in 2050, since the price of UK locally sourced
21 biomass chips (10 $\text{£}/\text{MWh}$) is much closer to the price of coal (7 $\text{£}/\text{MWh}$).

22 [Figure 6 about here.]

23 The cost of CO_2 captured was calculated by multiplying the LCOE ($\text{£}/\text{MWh}$)
24 by the annual electricity output (MWh/yr), then dividing by the annual

1 CO₂ emissions captured (tCO₂/yr). However, this varied very little over
2 time, since improved capital costs and plant efficiencies meant that both the
3 LCOE and the amount of CO₂ captured per year decreased in step, if it is
4 assumed that the plant power output remains constant. Alternatively, if the
5 plant feedstock input remains constant, then the amount of CO₂ captured
6 will be fixed, but the LCOE will fall as the annual electricity output rises
7 again, giving little change in the cost of CO₂ captured. As the cost of CO₂
8 captured varied only slightly over time; average 2010-2050 values have been
9 presented in Figure 6.

10 Given the dependency between LCOE and the cost of CO₂ captured,
11 Figure 6 shows several similarities to the trends in LCOE across the eight
12 technology combinations. The co-firing options exhibited the cheapest cost
13 of CO₂ captured (due to coal vs. pellet prices), with the switch between
14 biomass pellets and chips noticeably reducing the cost of CO₂ captured for
15 the other options. Interestingly, the 50 MW_e case with chips yielded very
16 similar cost of CO₂ captured across the board (range of 100-130 £/tCO₂),
17 since the slight differences in LCOE were balanced by the different amounts
18 of CO₂ captured (with lower efficiency plants capturing more CO₂ whilst
19 they generated the target 50 MW_e).

20 [Figure 7 about here.]

21 In order to evaluate the cost of CO₂ avoided, the comparator technology
22 was chosen to be an unabated coal power plant (from the relevant decade)
23 for the benchmarking exercise. The cost, efficiency and emissions data for
24 unabated coal combustion power plants were used from previous published

1 data [51]. The choice of a different comparator technology such as a coal
2 power plant with CCS or a dedicated biomass power plant (without CCS),
3 both more expensive options, would further reduce the cost of CO₂ avoided
4 reported in the TESBiC study.

5 The cost of CO₂ avoided only dropped slightly over time; hence again only
6 average 2010-2050 values were presented. Figure 7 shows a tight grouping
7 when using a common scale of 50MWe, with costs of avoided CO₂ between
8 60-90 £/tCO₂ when using pellets (30-65 £/tCO₂ were obtained when using
9 chips). The feedstock costs dominate, so those technologies that maximise
10 the use of low-cost chips (i.e. the dedicated biomass technologies) were able to
11 achieve the lowest costs of CO₂ avoided. Bio chem loop appears to potentially
12 be the most attractive technology in both cases (by quite some distance),
13 although the uncertainty bars are large for this earlier stage technology.

14 From a TRL perspective, the eight shortlisted Biopower CCS technologies
15 (out of twenty eight in total) represent a wide range of current TRLs (Tech-
16 nology Readiness Levels) i.e. from TRL4 (bench-scale test rig) to TRL6-7
17 (demonstration). *Second generation* capture technologies such as cofire carb
18 loop and bio chem loop currently have low TRLs (4 to 5), as is evident from
19 the limited (fewer than 10) number of bench scale and pilot scale plants,
20 with a maximum plant capacity of 3 MW_{th}. These technologies (a majority
21 of which are operated with coal feedstocks at present) yielded higher uncer-
22 tainties in their techno-economic estimates as compared to the *first genera-*
23 *tion* capture technologies such as amine scrubbing and oxyfuel combustion
24 with higher TRLs of 6 to 7. For lower current TRL technology options,
25 the TESBiC data from existing pilot plants and demonstrations helped in

1 identifying the key technical and commercial gaps and challenges that ex-
2 ist for the selected Biopower CCS technologies. To present an example, for
3 dedicated biomass chemical looping combustion (bio chem loop), some of
4 the unknowns associated with the identification of an optimal oxygen carrier
5 material suited for biomass feedstocks, the stability and lifetime of the car-
6 rier, the attrition rates at large scales and achieving higher gas conversion
7 efficiency were highlighted. These factors were classified as having ‘high un-
8 certainty’, whereas factors such as incompleteness of the flowsheet at large
9 scales and high temperature solid circulation rates were identified as having
10 ‘medium uncertainty’.

11 An outline development roadmap for each of the technologies were also
12 prepared as part of the TESBiC study. In the case of the more developed
13 Biopower CCS technologies, the route to further development after demon-
14 stration of the capture technology on a coal-fired plant would involve de-
15 ployment of the capture technology at a commercial scale on a coal plant co-
16 firing biomass, or demonstration on a dedicatd biomass plant. The roadmaps
17 for many of the Biopower CCS technologies are closely tied to the develop-
18 ment of fossil CCS technology. For the less well developed capture tech-
19 nologies (chemical and carbonate looping), fairly conventional development
20 roadmaps, involving component testing, small and large pilot scale testing,
21 and larger scale demonstration activities have been defined.

22 **6. Conclusions**

23 The TESBiC study focused on assessing twenty eight technology combi-
24 nations involving biomass fuelled power generation combined with CO₂ cap-

1 ture (Biopower CCS). Based on their deployment potential by 2050 and the
2 system-level TRL (Technology Readiness Level) progression criteria, tech-
3 nologies were short-listed for further analysis. These eight options repre-
4 sented a wide range of current TRLs i.e. from TRL4 (bench-scale test rig) to
5 TRL6-7 (demonstration). Base case process flowsheet models (mass and en-
6 ergy balances) were developed for each of the eight technology combinations
7 by employing a high-level process description for Nth-of-a-kind plants. The
8 base case models were then utilised to generate fast-response surrogates or
9 meta models for techno-economic outputs (CAPEX, non-fuel OPEX, genera-
10 tion efficiency, LCOE, cost of CO₂ captured and avoided) as functions of the
11 four input parameters (co-firing levels, extent of carbon capture, nameplate
12 and operating capacities).

13 Wherever a direct comparison was feasible (for plants with an unabated
14 equivalent), it was observed that the net efficiency penalty due to carbon
15 capture varied in the range of 6 to 15 percentage points, whereas the specific
16 investment costs (CAPEX) increased in the range 45% to 130%, with annual
17 operating and maintenance costs growing by 4% to 60%. At 250 MW_e, the
18 technology combinations were observed to be tightly grouped, almost lying
19 completely within each other's uncertainty bounds. In general terms, the
20 plant scale (MW_e), rather than the choice of technology is the principal driver
21 of CAPEX (£/MW_e). The co-firing %, i.e. the weighted feedstock cost, is one
22 of the key drivers of LCOE, with dedicated biomass options using expensive
23 pellets always having significantly higher LCOE than co-firing with cheap
24 coal. At 50 MW_e, the LCOE results over the period 2010 to 2050 exhibited
25 three distinct groupings: the first with low efficiency bio amine and bio oxy

1 with the highest LCOE, then the higher efficiency bio IGCC, bio chem loop
2 and cofire carb loop options with a moderate LCOE, and the cofiring options
3 with amine, oxy and IGCC with the lowest LCOE on account of the cheap
4 coal prices. Although the dedicated biomass technologies yield higher LCOE
5 values and costs per tonne of CO₂ captured, the major advantages of these
6 technology combinations, however, are that they do not involve fossil fuel
7 utilisation and that they offer very significant negative CO₂ emissions per
8 kWh generated at relatively modest scales. Using biomass pellets for the
9 cofiring and dedicated technology options at 50 MW_e capacity, the average
10 values over the period 2010 to 2050 for the costs of CO₂ captured were
11 observed to be in the range of 100-190 £/tCO₂ and for the costs of CO₂
12 avoided to be in the range of 60-90 £/tCO₂.

13 Presently, there are also no financial incentives available (anywhere in the
14 world) specifically for the generation of electricity with negative CO₂ emis-
15 sions - current policies either only penalise positive emissions, or incentivise
16 zero emissions. The data collected during the TESBiC project indicates that
17 the most significant barriers to the deployment of Biopower CCS technologies
18 will be economic and regulatory in nature, rather than technical, assuming
19 fossil CCS technologies are successfully proven at scale. Furthermore, estab-
20 lishing sustainable biomass supply chains with low upstream emissions (and
21 few indirect impacts on existing land use and carbon stocks) and availabil-
22 ity and suitability of CO₂ sequestration sites are important issues that would
23 need to be considered for the development and deployment of Biopower CCS.
24 More detailed engineering studies are recommended to help reduce the uncer-
25 tainties in the cost estimates across the eight technology combinations. Such

1 studies followed by pilot and demonstration activities involving BioPower
2 CCS technologies naturally form the next step towards rapidly reducing CO₂
3 emissions from the power sector, whilst keeping open the option of developing
4 low-cost, scalable negative emissions technologies in case of lack of mitigation
5 action and climate change overshoot.

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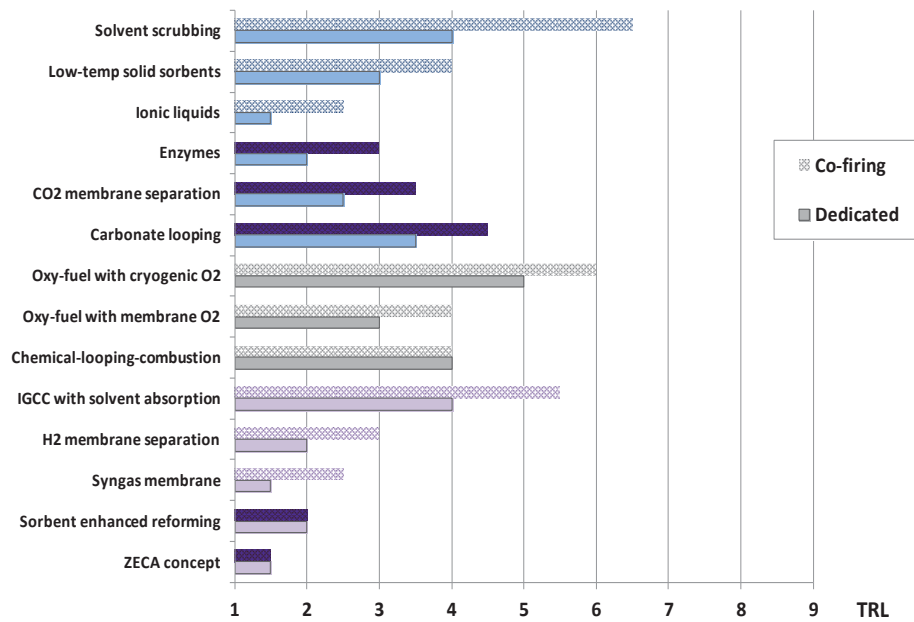


Figure 1: *Current technology readiness levels (TRL) for CCS technologies.*

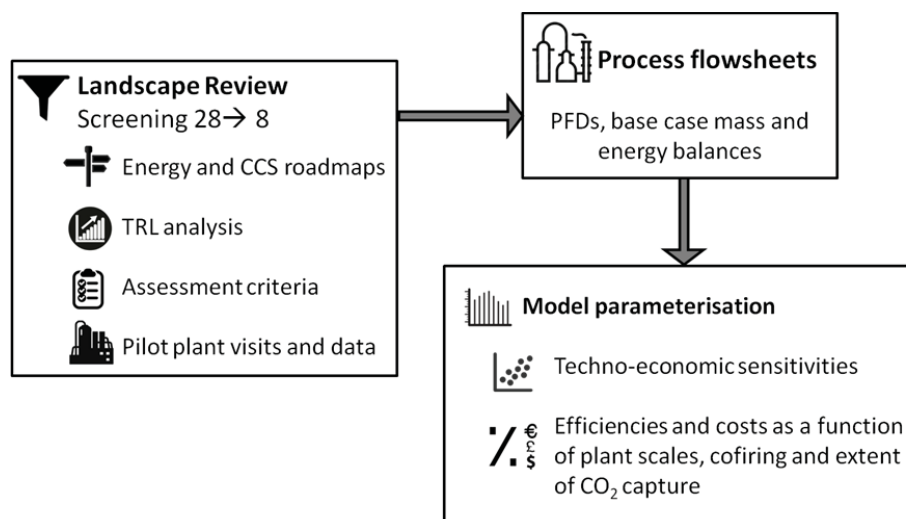


Figure 2: *TESBiC work-flow.*

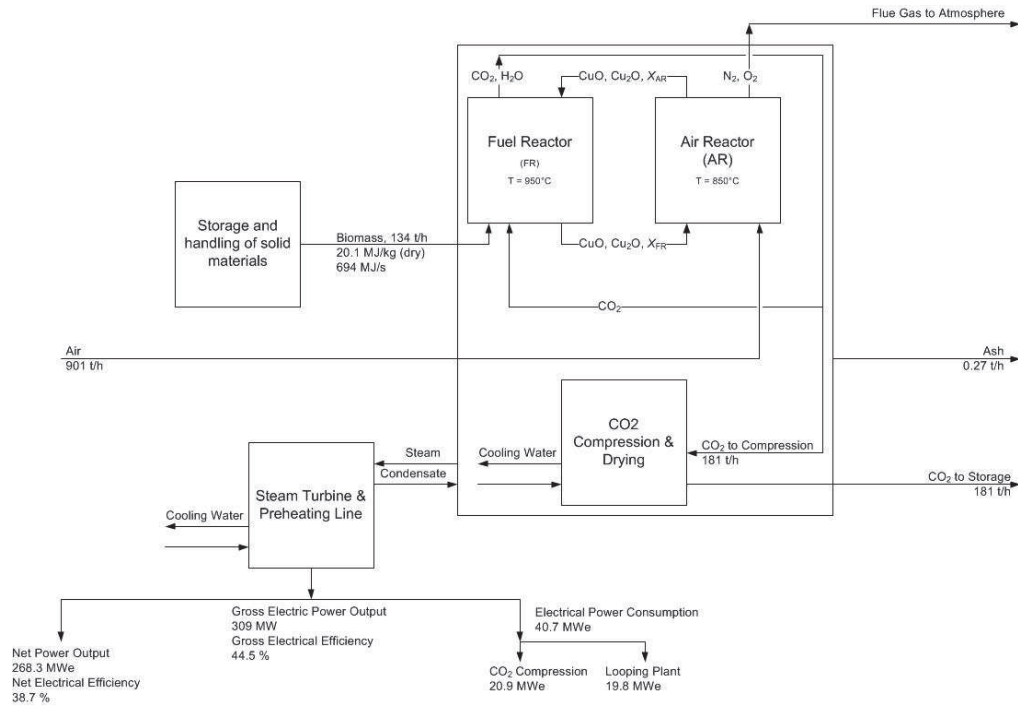


Figure 3: A high-level process flow diagram for dedicated biomass chemical looping combustion (bio chem loop).

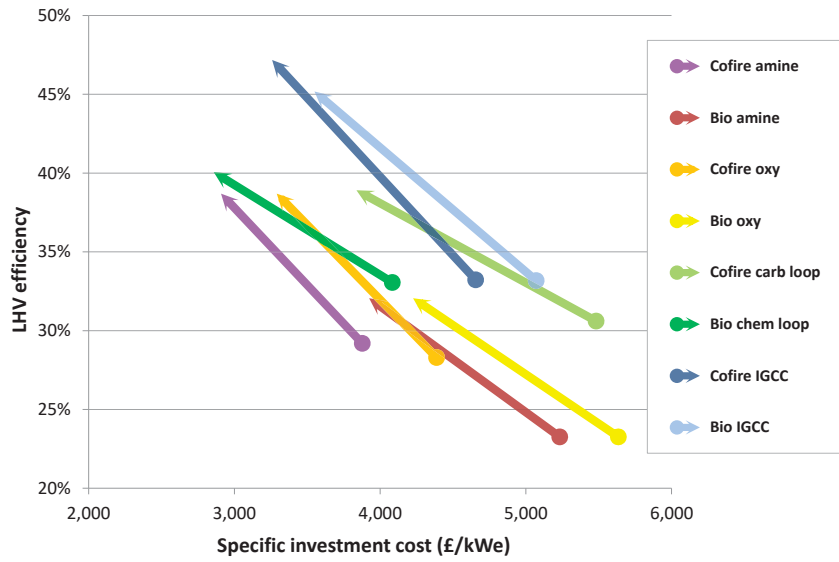


Figure 4: *LHV efficiency vs. “Nth-of-a-kind” specific investment costs for eight Biopower CCS technology options (dots indicate 2010 values and arrow heads indicate estimates for 2050).*

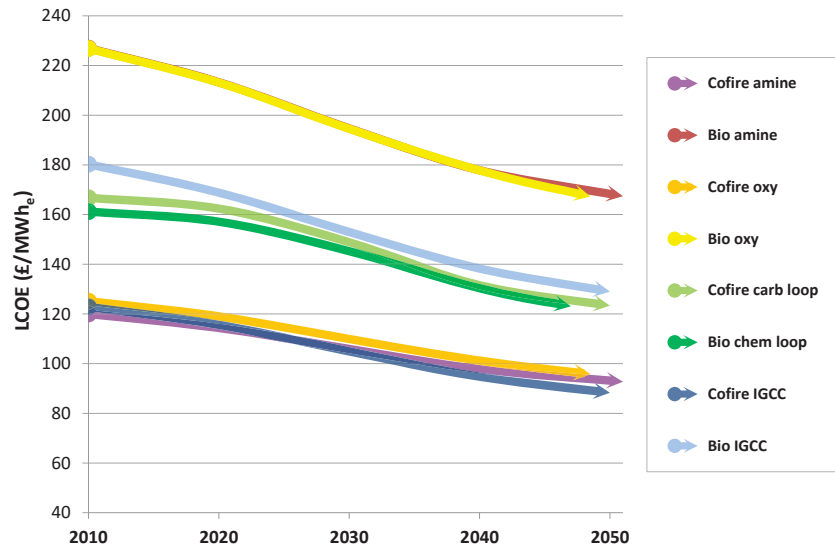


Figure 5: *LCOE for the eight Biopower CCS technology options up to 2050, at 50 MW_e.*

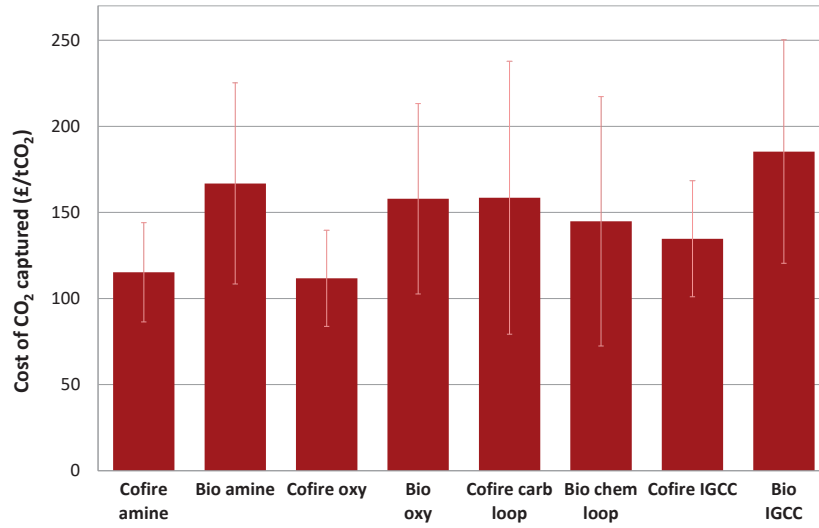


Figure 6: *Cost of CO₂ captured for the eight Biopower CCS technology options at 50 MW_e.*

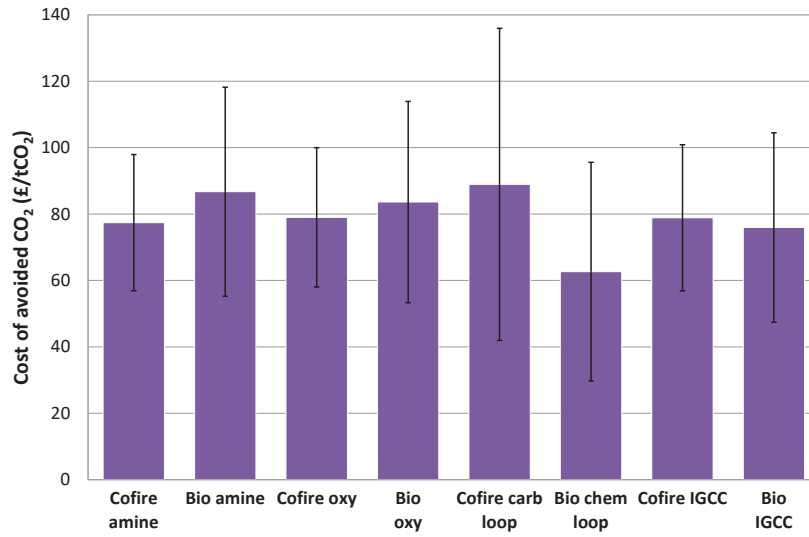


Figure 7: *Cost of CO₂ avoided for the eight Biopower CCS technology options at 50 MW_e.*